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Estuarine and Ocean Survival of Northeastern Pacific Salmon

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REGIME SCALE CLIMATE FORCING OF SALMON POPULATIONS IN THE NORTHEAST PACIFIC—SOME NEW THOUGHTS AND FINDINGS

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Recent work (Hare and Francis 1992, Francis and Hare 1994, Hare and Francis 1995, Hare 1996) has shown that Alaska salmon population production responds to regime-scale (interdecadal) climate forcing, manifesting itself in low frequency and rather abrupt jumps (Fig. 1) which correspond very closely to similar abrupt shifts in North Pacific atmosphere and ocean climate (Fig. 2). Careful analysis reveals that

1. This connection between atmosphere/ocean physics and salmon production occurs early in the salmon marine life history.
2. To date, connections between indices of climatic variability and salmon production have been found at the regime (interdecadal) scale, but not at the interannual scale.

The signature of these climatic regime shifts is reflected in a number of atmospheric and oceanic variables, the most noteworthy of which are winter sea level pressure (SLP) and spring sea surface temperature (SST) over a large region of the North Pacific. During the 20th century, there appear to have been four interdecadal regimes (Fig. 2, top) in the coupled atmosphere/ocean system of the North Pacific: 1900-24, 1925-46, 1947-76, 1977-present (Francis et al. in prep., Hare 1996). The lower two panels of Figure 2 show differences in mean winter SLP and SST between the two most recent regimes. These two patterns characterize what we call the Pacific Decadal Oscillation which, when positive, is reflected in a deep winter Aleutian low pressure system and a bipolar SST anomaly pattern with warm SST anomalies along the Northeast Pacific coast and cold SST anomalies in the central Pacific. These patterns are derived, analyzed, and discussed in detail by Hare (1996).

The objective of this paper is to discuss recent findings on the effects of regime-scale climate changes on upper ocean dynamics and apparent responses in phytoplankton and zooplankton production in both the California and Alaska Current regions of the Northeast

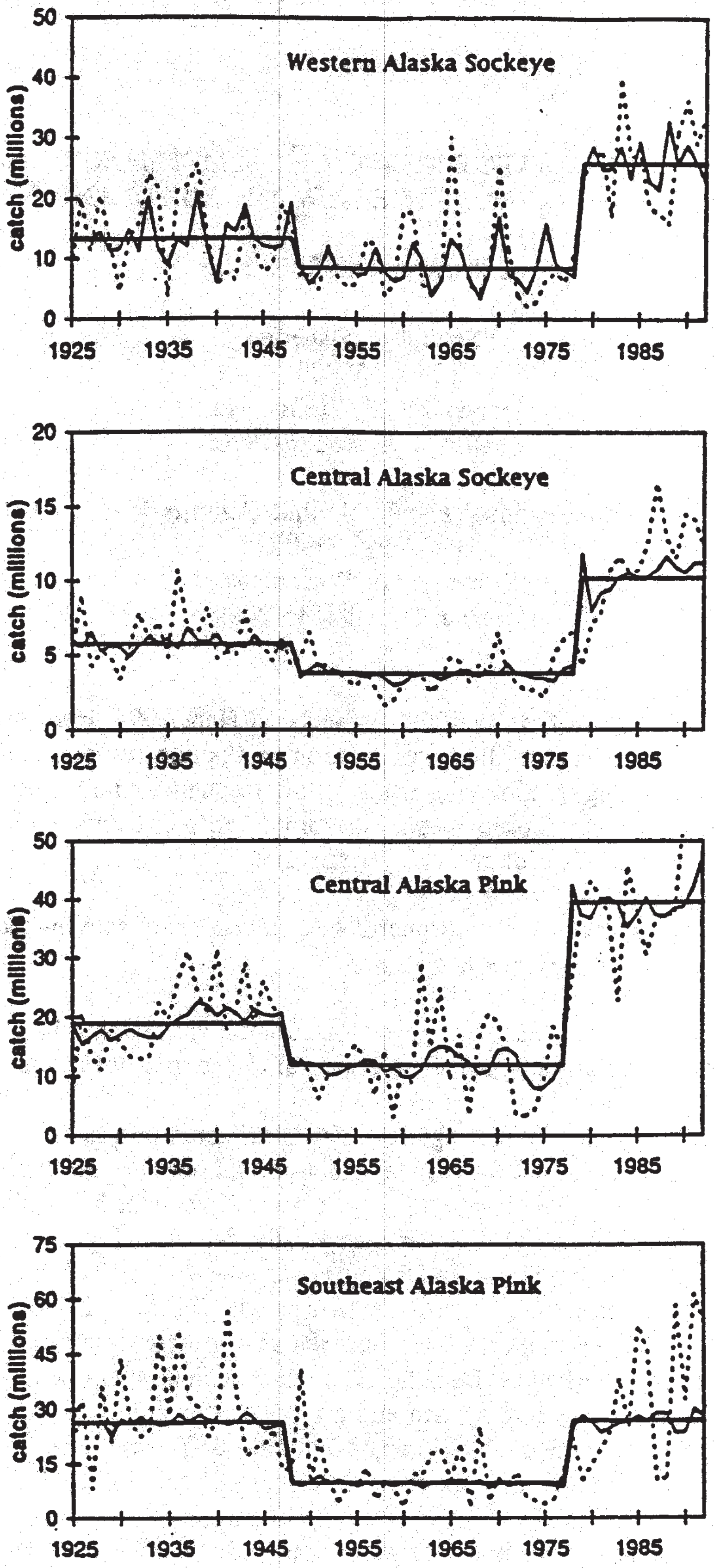
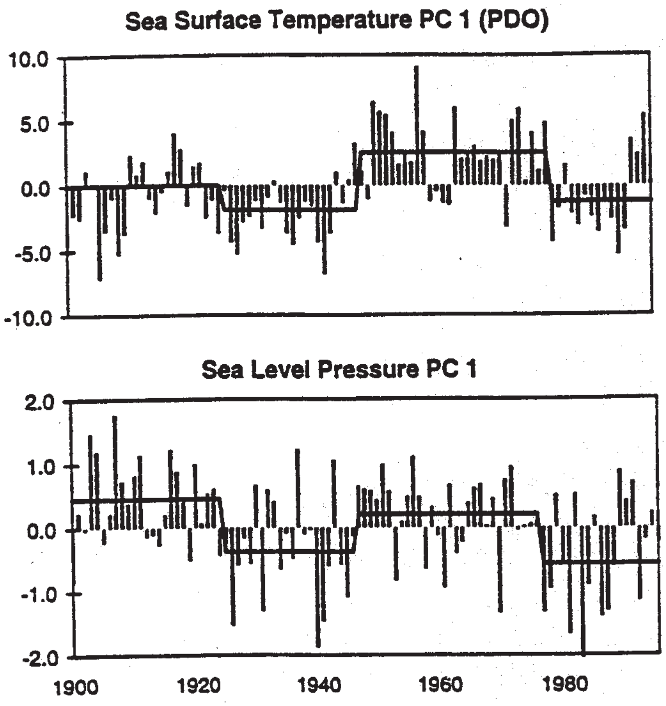


Figure 1. Time history (dashed lines), intervention model fits (thin solid lines), and estimated interventions (thick solid lines) for Alaska salmon time series (from Francis and Hare 1994).



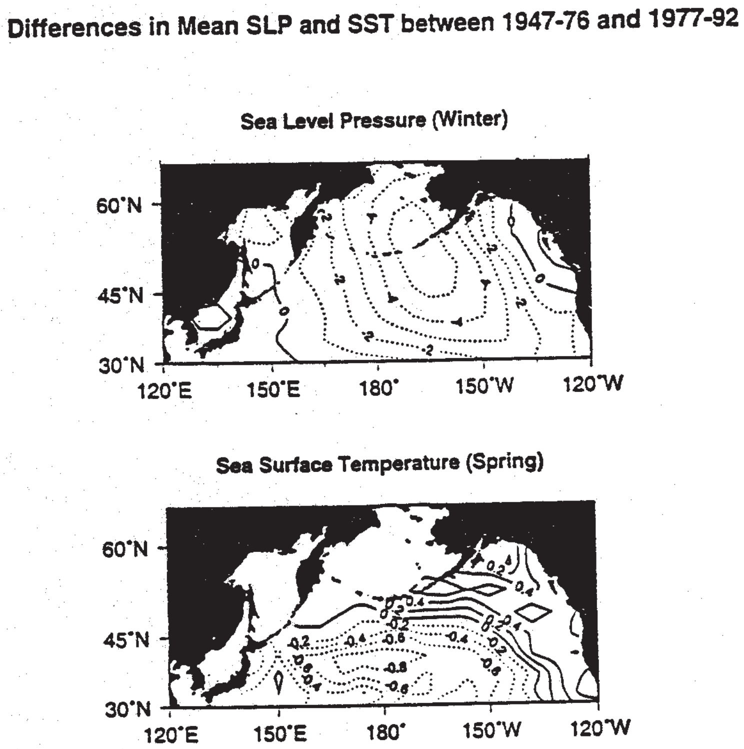


Figure 2. Two indicators of large-scale, long-term climate variability over the North Pacific in the 20th century. The top two panels show major components of variability of North Pacific winter sea surface temperature (SST) (Pacific Decadal Oscillation, PDO) and winter sea level pressure (SLP) along with intervention model fits. The two bottom panels illustrate winter atmospheric and spring oceanic effects of the 1976/77 climate regime shift (Hare 1996).

Pacific. These results have major implications concerning mechanisms linking the observed decadal-scale climate response of Northeast Pacific salmon to their ocean environment.

Recent Findings

A Model

Over the past few decades, a conceptual model has developed which relates atmospheric circulation in the North Pacific to variations in biological production in the large oceanic ecosystems (Fig. 3) of the Northeast Pacific (Ware and MacFarlane 1989). Wickett (1967), Chelton and Davis (1982), and Chelton (1984) were the first to speculate that the intensities of the flows in the Alaska and California Currents fluctuate in opposition to each other. That is, when one of the currents is stronger than normal, the other is weaker. They hypothesized that these north-south shifts in the bifurcation of the Subarctic Current (West Wind Drift) could be forced by physical factors occurring in the western or central Pacific. Taking this one step further, and based on marine biological indices, Hollowed and Wooster (1992) and Francis (1993) have characterized two alternating interdecadal states of atmospheric and oceanic circulation in the Northeast Pacific which result in very different components of fisheries production (e.g., groundfish, salmon) in these two major coastal domains. Hollowed and Wooster (1992) have characterized two alternating “warm” and “cool” states lasting 6 to 12 years each. Hare and Francis (1992), Francis (1993), Francis and Hare (1994), and Hare and Francis (1995) find similar although longer periods (25 to 35 years) of oscillating “warm” and “cool” regimes which relate very closely to the production dynamics of Alaska salmon (Figs. 1 and 2). In addition, Francis (1993) speculated that the interdecadal dynamics of salmon production in these two oceanic domains is inversely correlated.

How has this model fared or changed in recent years? In what follows, we present both biological and physical results which expand and change our understanding of how interdecadal climate change affects the dynamics of marine biological production in the Northeast Pacific.

Biology

Perhaps the major breakthroughs in terms of changing our thinking have related to studies of phytoplankton and zooplankton production in the Northeast Pacific and their responses to interdecadal climate forcing. The three major studies reported in this section (Brodeur and Ware 1992, Polovina et al. 1995, Roemmich and McGowan 1995) focused on changes in plankton production which occurred in response to the Northeast Pacific climatic regime shift of 1976-77 (Miller et al. 1994).

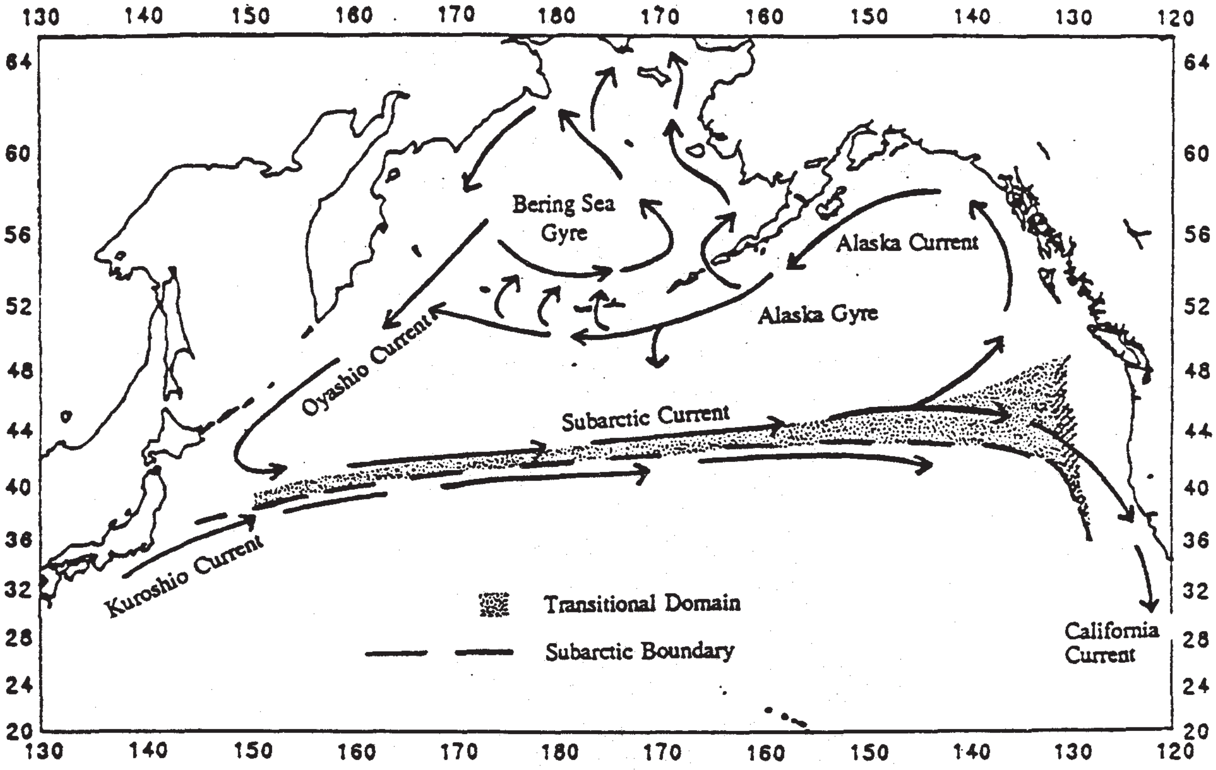


Figure 3. Relevant large-scale upper-level physical oceanography of the Subarctic North Pacific and Bering Sea (Francis and Hare 1994).

Venrick et al. (1987) showed significant shifts in phytoplankton production (integrated chlorophyll *a*) just north of Hawaii at about the time of the 1976-77 regime shift (Fig. 4). Subsequent analysis (Venrick 1994) revealed that his response was due to increased phytoplankton production in deep water (75-200 m) in response to a shift in ocean mixing and a deepening of the mixed layer. Polovina et al. (1995) further supported this and reported, associated with the 1976-77 regime shift and intensification of the Aleutian low pressure system, a 30-80% deepening of the winter and spring mixed layer in the Subtropical Domain (Northwestern Hawaiian Islands) and central Transition Zone (Emperor Seamounts) and a 20-30% shoaling of the mixed layer in the northern Subarctic Domain (Gulf of Alaska) (Fig. 5). Based on modeling of phytoplankton response to these changes, Polovina et al. (1995) speculated that these physical conditions would increase primary and secondary production in the northern Subtropical and northern (central) Subarctic Domains and decrease them in the Transition Zone.

Brodeur and Ware (1992), Brodeur et al. (1996), and Roemmich and McGowan (1995) have shown that zooplankton production in the central Subarctic Domain (central Gulf of Alaska) and Coastal Upwelling Domain (California Current) seems to have responded in opposite directions to the 1976-77 regime shift. In the central Subarctic Domain, summer zooplankton biomass more than doubled between the late 1950s and the 1980s (Brodeur and Ware 1992, Brodeur et al. 1996, Fig. 6). The mechanism proposed to underlie the interpretation of these phenomena involves variation in the circulation of the Subarctic Gyre in the Northeast Pacific—a speeding up and slowing down of the Subarctic and Alaska Currents. This would affect both Ekman pumping at the center of the gyre, leading to increased upwelling and divergence in the center, and advection (transport of nutrients, phytoplankton, zooplankton) around the circumference of the gyre. Associated with this would be a shoaling of the euphotic zone (mixed layer depth) and a resultant increase in the exposure of phytoplankton cells to light.

On the other hand, in the southern Coastal Upwelling Domain, the biomass of macrozooplankton has decreased by as much as 70% between the early 1950s and the early 1990s (Roemmich and McGowan 1995, Fig. 7). The authors provide several mechanistic hypotheses for their observations. First, they suggest that the coastal warming associated with the 1976-77 regime shift may have caused increased stratification in the California Current, a sharper thermocline with less vertical displacement of nutrient-rich waters due to wind stress (coastal upwelling), and a resultant decrease in the fraction of the year when wind stress is strong enough to lift nutrient-bearing waters to the sea surface near the coast. Second, they speculate that a climate-induced shift in ocean circulation, such as the bifurcation of the west wind drift (Subarctic Current), might import warmer water into the California Current, thus decreasing the supply of either nutrients or the volume of zooplankton carried by the California Current.

Both of these findings are consistent with the earlier results of Wickett (1967) who studied the interannual variation in zooplankton volumes off California, in the western Bering Sea, and at Ocean Station P (lat. 50°N, long. 145°W) in the central Gulf of Alaska

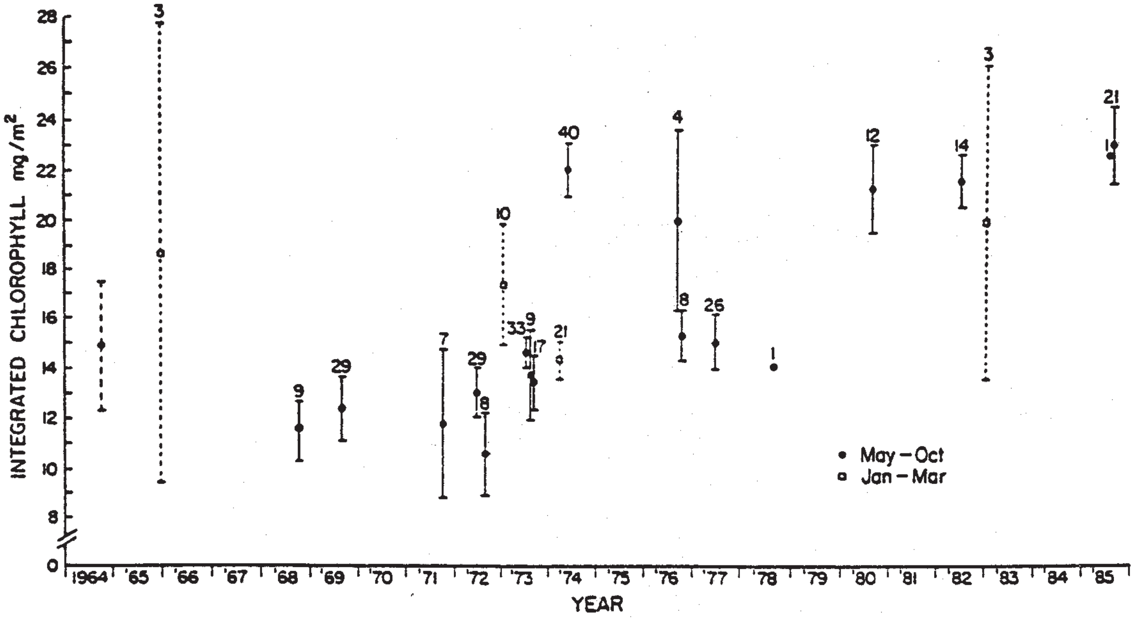


Figure 4. Index of phytoplankton in the central North Pacific (observations of integrated chlorophyll *a*). Bars indicate the 95% confidence intervals of the mean; the number of observations is shown above each bar. Winter values (open squares) and values before 1968 are excluded from the analysis (Venrick et al. 1987).

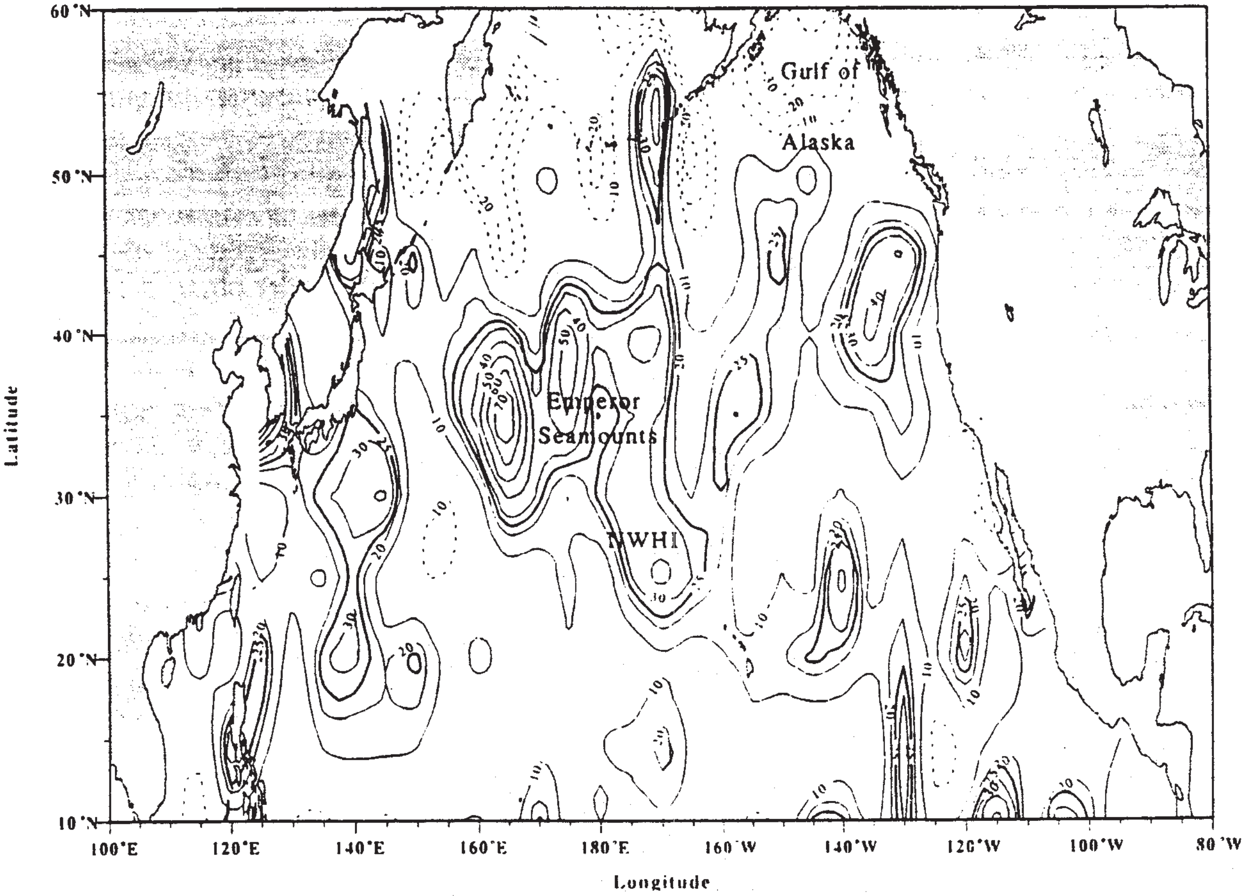


Figure 5. Percent change in mean winter and spring mixed layer depth (MLD) between 1977-88 and 1960-76 relative to 1960-76 levels. Shading for 1977-99 MLD which are more than 25% deeper than 1960-76 MLD. Dashed contours are negative values (Polovina et al. 1995).

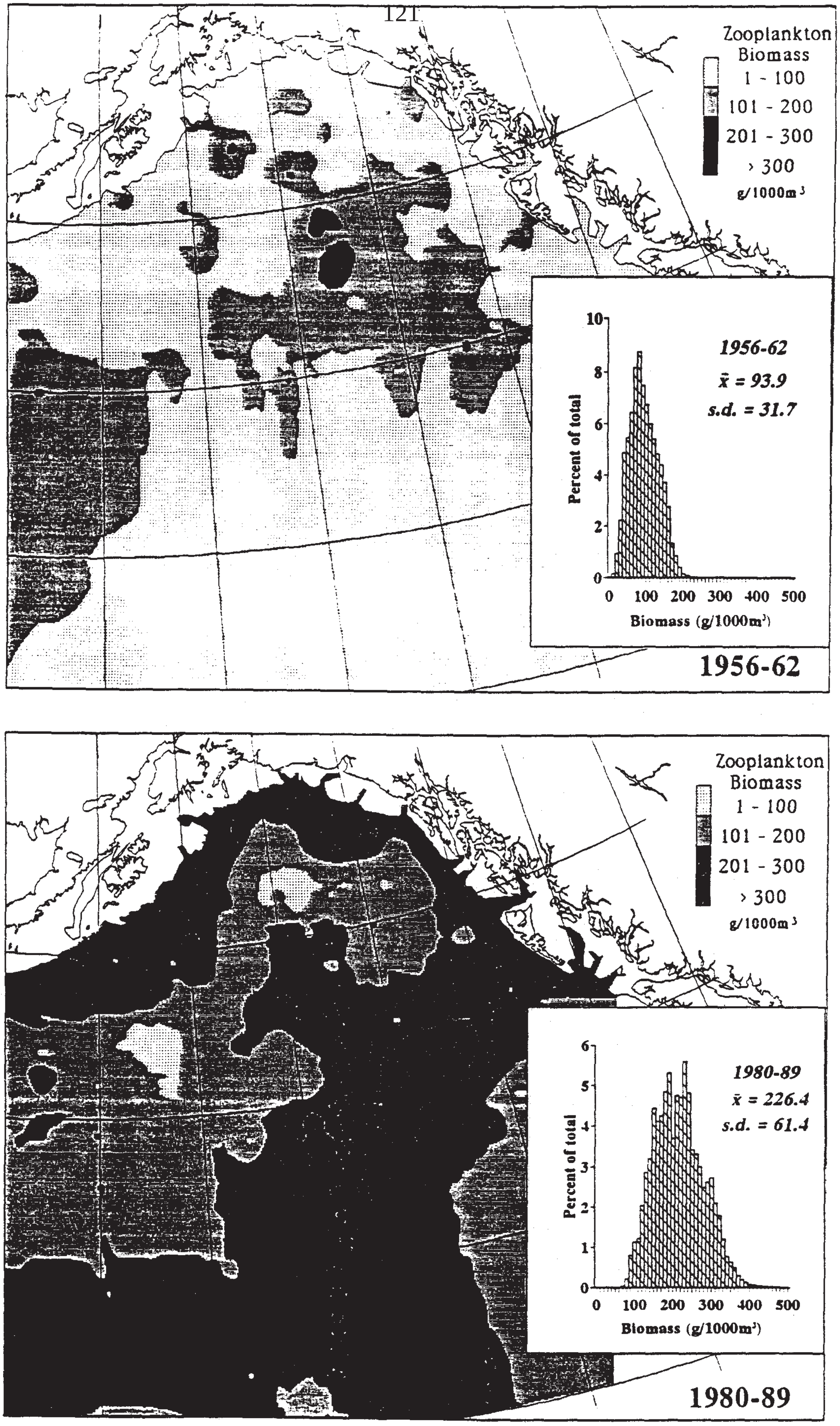


Figure 6. Large-scale distribution of zooplankton biomass from sampling during the 6-week period beginning June 1 for the period 1956-62 (top) and 1980-89 (bottom) (Brodeur et al. 1996).

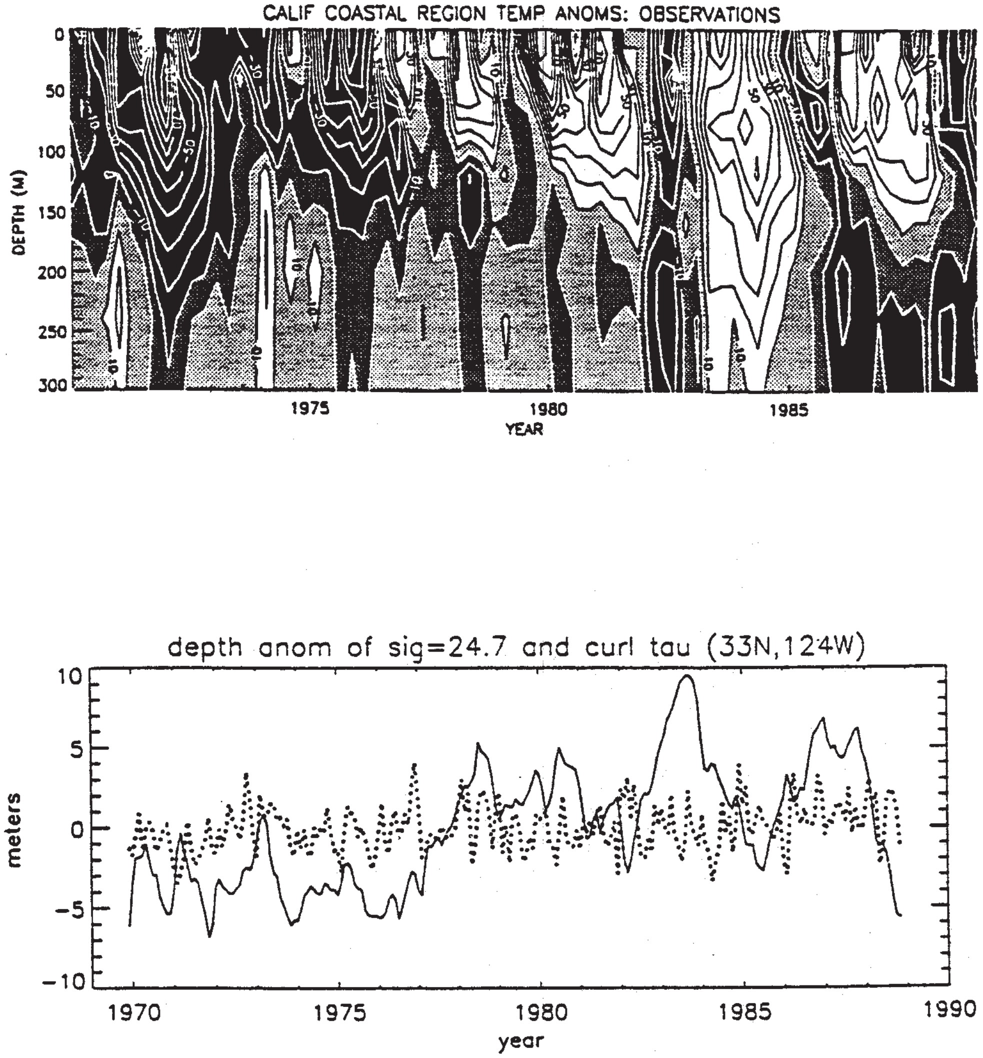


Figure 7. Callifornia Cooperative Oceanic Fisheries Investigations Line 90 (A) and corrected annual averages of zooplankton volume (B) since 1950 (Roemmich and McGowan 1995).

during the 1950s and early 1960s. By studying the relative abundances of zooplankton in these regions and relating them to zonal and meridional components of surface winds in a region upstream of the bifurcation of the Subarctic Current, Wickett found that a major cause of zooplankton variation downstream from the division point (bifurcation of the Subarctic Current into the California and Alaska Currents) is the change in the proportion of surface-layer, wind-driven water (Ekman transport) that is swept southward (escaping) out of the subarctic circulation. The implication is that zooplankton and nutrients are carried with the surface waters and that forcing conditions (surface winds) which favor a high “escapement” of subarctic water into the California Current will increase zooplankton production in that region and decrease it in the region of the Alaska Current.

Physics

Although there is indirect biological evidence for the ocean circulation models first proposed by Hollowed and Wooster (1992) and Francis (1993), the physical evidence is very hard to come by. Five recent papers do, however, begin to shed light on the issue and speculate considerable modification to the above model. Tabata (1991), in reexamining the Chelton and Davis (1982) premise, found a correlation between the coastal component of the Alaska Current and California sea level, particularly during El Niño years. He attributed this correlation, however, to the coastal currents being in phase from Canada to California rather than to changes in the bifurcation of the Subarctic Current. Kelly et al. (1993) analyzed sea-surface height anomalies for the Northeast Pacific over a 2.5-year period. Their results tended to support those of Chelton and Davis (1982) that the California and Alaska Current systems fluctuate “out of phase,” coinciding with variations in wind-stress curl in the North Pacific and subsequent diversion of flow from the Alaska Gyre into the California Current as well as with some aspects of El Niño Southern Oscillation (ENSO) dynamics. Van Scoy and Druffel (1993), in an analysis of tritium (^{3}H) concentrations in seawater from Ocean Station P and a station in the southern California Current, suggested increased advection of subpolar water into the California Current during non-El Niño years and that ventilation of the Alaska Gyre (intensification) occurs during El Niño years. Lagerloef (1995), in his analysis of dynamic topography in the Alaska Gyre during 1968-90, suggested that after the well-documented climatic regime shift of the late 1970s, the Alaska Gyre was centered more to the east and its circulation appeared weaker after the shift than before. The implication is that the intensification of the winter Aleutian low pressure system associated with the regime shift did not result in a spinup of the Alaska Gyre. Finally, Miller (1996) reviews some recent advances in large-scale modeling of the California Current and its interaction with basin-scale circulation and forcing. He reports the significant deepening of the thermocline off California after the 1976-77 regime shift (similar to Roemmich and McGowan 1995) and attributes this to basin-scale changes in wind-stress curl. This is achieved at two time scales—the first at the decadal and North Pacific Gyre scale forced by significant deepening and weakening of the Aleutian low pressure system, and the second at the interannual ENSO scale forced by waves propagating through the ocean from the tropics.

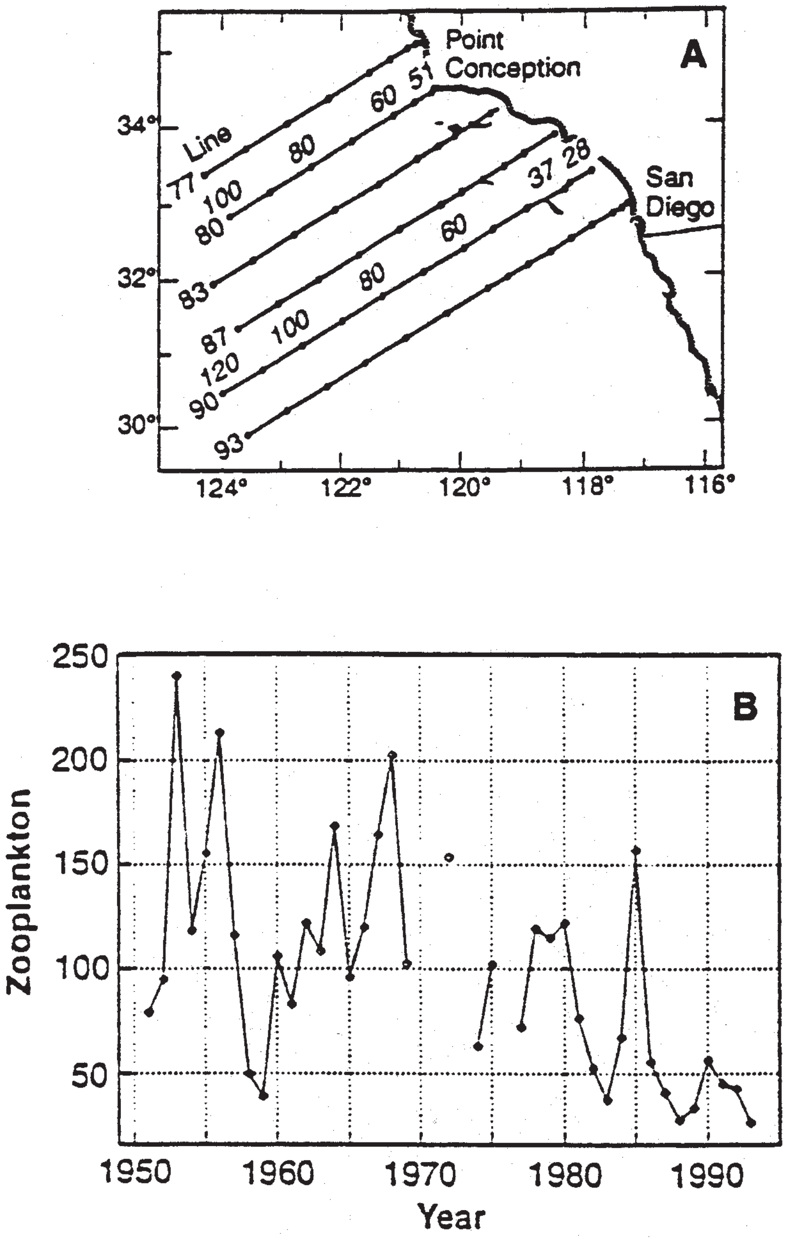


Figure 8. Top: Observed temperature anomalies averaged over the region long. 130-120°W, lat. 25-45°N from the surface to 300-m depth from 1970-88. Contour interval is 0.1°C with darker shades cooler and lighter shades warmer. Bottom: Depth anomalies (solid) of model isopycnal layer (s 24.7) at a grid point off the California coast. Positive anomalies indicate a deeper thermocline at mean depth of roughly 180 m. Local wind-stress curl anomalies (dotted) at the same point (Miller et al. 1996).

Miller et al. (1996) and Miller (1996) support the findings of Roemmich and McGowan (1995) and report both decadal and interannual signals in the dynamics of the thermocline off the California coast (Fig. 8). The first signal is a thermocline deepening associated with decadal-scale changes in the subtropical gyre and its mixed layer structure as influenced by changes in gyre-scale wind forcing (wind-stress curl). The second signal occurs at the ENSO time scale (3-7 years) and is driven by waves propagating through the ocean, presumably from the tropics. One can see the effects of both of these processes in the dynamics of mixed layer temperature profiles as well as thermocline depth anomalies (Fig. 8). The results of Enfield and Allen (1980) tend to support this and indicate that the region off central California (San Francisco) may be a dividing point between locations to the south where sea level is influenced by anomalies of equatorial origin (related to fluctuations in the Southern Oscillation) and locations to the north where sea level is influenced strongly by local wind-stress anomalies resulting from energetic winter storms (related to the winter Aleutian low pressure phenomenon). Therefore, the higher frequency dynamics in mixed layer depth and temperature reported by Miller et al. (1996) and Miller (1996) for a region off southern California (Fig. 8) may not be as evident in more northerly components of the California Current. In fact, Freeland (1990) reported that coastal British Columbia sea surface temperatures showed very little coherence with the ENSO signal.

Finally, Miller (1996) also reported that after the 1976-77 regime shift there appeared to be a stronger than normal northward flow into the central Gulf of Alaska but little change in (flow into) the California Current system.

Discussion

Clearly much has been learned since 1982 (when Chelton first proposed his model) concerning the relation between atmosphere/ocean physics and Northeast Pacific salmon production. Based on the results summarized above, the following seems fairly clear:

1. The major climate influence on salmon production occurs at the decadal time scale, early in the marine life history, and in a bottom-up fashion through physical influences on primary and secondary production.

2. Plankton production seems to be influenced at the decadal (regime) scale by major climate-induced changes in the structure of the mixed layer. These influences appear to operate in opposite directions in the California Current and Alaska Current oceanic domains.

3. The farther south, the stronger is the influence of climate on biological production at the higher-frequency ENSO scale. For example, the coastwide spike in Pacific Northwest salmon production which seemed to affect cohorts entering the ocean either in late 1984 or early 1985 could have resulted from a 1985 rebound to the

1982-83 El Niño (Fig. 8—rapid cooling of the ocean and corresponding deepening of the mixed layer off California in 1985).

4. The effects of ocean circulation, particularly as they relate to the relative intensities of advection of subarctic water into the California and Alaska Currents, are less clear. Recent evidence points to a more complicated picture than the first speculated by Chelton (1984) at the first of these conferences in 1983. What does appear to be happening is that if advection and circulation are important, it is their effects on upper ocean structure (mixed layer depth, temperature) which, in turn, directly affects biological production.

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